COMPASS Results on Pion and Kaon Multiplicities from SIDIS on Proton Target

M. Stolarski
LIP

On behalf of the COMPASS Collaboration

19 X 2023
COMPASS at CERN

LHC

COMPASS

SPS
**COMPASS Spectrometer 2016**

- **COLLABORATION**
  - about 210 physicists
  - 27 institutes

- **DETECTOR**
  - two stage spectrometer
  - 60 m length
  - about 350 detector planes

- **TARGET**
  - Liquid H target
  - 250 cm - total length

- **BEAM**
  - $\mu^\pm$ at 160 GeV/c

- **FEATURES**
  - angular acceptance: $\pm 180$ mrad
  - track reconstruction: $p > 0.5$ GeV/c
  - identification $h, e, \mu$: calorimeters and muon filters
  - identification: $\pi, K, p$ (RICH) $p > 2, 9, 18$ GeV/c respectively

**TARGET**
- Liquid H target
- 250 cm - total length

**BEAM**
- $\mu^\pm$ at 160 GeV/c

**FEATURES**
- angular acceptance: $\pm 180$ mrad
- track reconstruction: $p > 0.5$ GeV/c
- identification $h, e, \mu$: calorimeters and muon filters
- identification: $\pi, K, p$ (RICH) $p > 2, 9, 18$ GeV/c respectively

**COLLABORATION**
- about 210 physicists
- 27 institutes

**DETECTOR**
- two stage spectrometer
- 60 m length
- about 350 detector planes

**TARGET**
- Liquid H target
- 250 cm - total length

**BEAM**
- $\mu^\pm$ at 160 GeV/c

**FEATURES**
- angular acceptance: $\pm 180$ mrad
- track reconstruction: $p > 0.5$ GeV/c
- identification $h, e, \mu$: calorimeters and muon filters
- identification: $\pi, K, p$ (RICH) $p > 2, 9, 18$ GeV/c respectively
Motivation

- Fragmentation functions (FF(s), $D_q^h$) describe parton fragmentation into hadrons.
- FFs are needed in analyses which deal with a hadron(s) in the final state.
- In Leading Order QCD $D_q^h$ describes probability density for a quark of flavour $q$ to fragment into a hadron of type $h$.
- The cleanest way to access FFs is in $e^+e^-$ annihilation. However,
  - only sensitive to the sum of $q + \bar{q}$ fragmentation
  - flavour separation possibilities are limited.
- In the SIDIS ($\mu^\pm + p \to \mu^{\pm'} + h + X$) data, FF are convoluted with PDFs. However,
  - possibility to separate fragmentation from $q$ and $\bar{q}$
  - full flavour separation possible.
- By studying $pp$ collisions with high $p_T$ hadrons, access to gluon fragmentation functions.
- SIDIS data are crucial to understand quark fragmentation process.
Fragmentation studies in SIDIS can be done using hadron multiplicity data.

Hadron multiplicities are defined as number of observed hadrons per DIS event:

$$\frac{dM^h(x,z,Q^2)}{dz} = \frac{d^3\sigma^h(x,z,Q^2)/dx dQ^2 dz}{d^2\sigma^{DIS}(x,Q^2)/dx dQ^2}$$

Experimentally measured hadron multiplicities need to be corrected for various effects e.g.

- spectrometer acceptance and reconstruction program efficiency
- RICH efficiency and purity (for $\pi$ and $K$)
- radiative corrections
- diffractive vector meson production

COMPASS already published several articles based on isoscalar target data:

- PLB 764 (2017) 001
- PLB 767 (2017) 133
- PRD 97 (2018) 032006
- PLB 786 (2018) 390
- PLB 807 (2020) 135600

Today, preliminary results from the proton target are presented.
Correction due to radiative effects is a multiplicative factor to the multiplicity itself, and can be large, especially at low $x$ and high $y$.

The DJANGOH programme is used for RC simulations.

It was tested against COMPASS data and the TERAD program.

Some early results were shown already in 2019.
COMPASS was always showing results with and without our estimate for RC

Thus, new results can be easily implemented to older COMPASS multiplicity papers

Note: according to our present knowledge the data from PLB 764 (2017) 001 ($\pi^\pm, h^\pm$) need correction sometimes above 10%
Data Selection - Main Cuts

- DIS selection:
  - Reconstructed $\mu$ and $\mu'$,
  - $Q^2 > 1 \text{ (GeV/c)}^2$
  - $W > 5 \text{ GeV/c}^2$,
  - $0.1 < y < 0.7$, fraction of beam energy, $E$, carried by virtual gamma

- Hadron cuts:
  - $0.2 < z < 0.85$, fraction of the virtual photon energy carried by a hadron
  - $12 \text{ GeV/c} < p < 40 \text{ GeV/c}$, momentum cut due to RICH PID acceptance,
  - $\theta < 0.12$, $|dy/dz| < 0.08$, RICH acceptance

- Analysis is performed in 9 bins of Bjorken $x$, 5 bins of $y$ and 12 bins of $z$

- To avoid the "zero-acceptance" region, DIS sample is bin-by-bin restricted using

\[
\nu_{\text{max}} = \sqrt{\frac{p_{\text{max}}^2 + m_h^2}{z_{\text{max}}}},
\]
\[
\nu_{\text{min}} = \sqrt{\frac{p_{\text{min}}^2 + m_h^2}{z_{\text{min}}}},
\]

where $\nu = E - E'$,
- $p_{\text{min}} = 12 \text{ GeV/c}$ and $p_{\text{max}} = 40 \text{ GeV/c}$,
- $z_{\text{min}}$ and $z_{\text{max}}$ - correspond to the edges of a given bin in $z$ variable.
The bottom right plot shows the impact of the $\nu$ cuts on $z$ distribution

Total sample of events:

- DIS: 5.5M
- unidentified hadrons: 1.7M ($\pi$: 1.3M, K: 280k)
RESULTS
Multiplicities of $\pi^+$

$\frac{dM}{dz + \alpha}$

$0.01 < x < 0.02$

$0.02 < x < 0.03$

$0.03 < x < 0.04$

$0.04 < x < 0.06$

$0.06 < x < 0.10$

$0.10 < x < 0.14$

$0.14 < x < 0.18$

$x > 0.18$

COMPASS proton data preliminary

- $0.50 < y < 0.70, \alpha = 1.2$
- $0.30 < y < 0.50, \alpha = 0.9$
- $0.20 < y < 0.30, \alpha = 0.6$
- $0.15 < y < 0.20, \alpha = 0.3$
- $0.10 < y < 0.15, \alpha = 0.0$

M. Stolarski (LIP)

MAINZ 2023
Multiplicities of $\pi^-$

$\alpha$ + $\frac{z}{d} - \pi M < 0.01$

$\alpha$ + $\frac{z}{d} - \pi M < 0.06$

$\alpha$ + $\frac{z}{d} - \pi M < 0.10$

$\alpha$ + $\frac{z}{d} - \pi M < 0.14$

$\alpha$ + $\frac{z}{d} - \pi M < 0.18$

$\alpha$ + $\frac{z}{d} - \pi M = 1.2$

COMPASS proton data preliminary

- $0.50 < y < 0.70, \alpha = 1.2$
- $0.30 < y < 0.50, \alpha = 0.9$
- $0.20 < y < 0.30, \alpha = 0.6$
- $0.15 < y < 0.20, \alpha = 0.3$
- $0.10 < y < 0.15, \alpha = 0.0$
Multiplicities of $K^+$

COMPASS proton data preliminary

- $0.50 < y < 0.70, \alpha = 0.4$
- $0.30 < y < 0.50, \alpha = 0.3$
- $0.20 < y < 0.30, \alpha = 0.2$
- $0.15 < y < 0.20, \alpha = 0.1$
- $0.10 < y < 0.15, \alpha = 0.0$
Multiplicities of $K^-$

![Graph showing multiplicity distributions for different $z$ and $\alpha$ values]
Sum of Pion Multiplicities

- Let $D_{\text{fav,(unf)}} = D_q^h$ where $q$ is (not) the valence quark of $h$, in LO pQCD:

- For proton target in LO pQCD:
  \[
  \frac{dM^{\pi^+}}{dz} + \frac{M^{\pi^-}}{dz} = D_{\text{fav}} + D_{\text{unf}} - \frac{s+\bar{s}}{4u+4\bar{u}+d+d+s+\bar{s}} (D_{\text{fav}} - D_{\text{unf}}) \approx D_{\text{fav}} + D_{\text{unf}}
  \]

- For isoscalar target in LO pQCD:
  \[
  \frac{dM^{\pi^+}}{dz} + \frac{M^{\pi^-}}{dz} = D_{\text{fav}} + D_{\text{unf}} - \frac{2(s+\bar{s})}{5(u+\bar{u}+d+d)+2(s+\bar{s})} (D_{\text{fav}} - D_{\text{unf}}) \approx D_{\text{fav}} + D_{\text{unf}}
  \]

- Results for proton and isoscalar targets are expected to be very similar

- $D(Q^2, z) \rightarrow$ obtained from multiplicity sum is effectively independent of $x$

- $\mathcal{M}^{\pi^+} + \mathcal{M}^{\pi^-} = \int_{0.2}^{0.85} (\frac{dM^{\pi^+}}{dz} + \frac{dM^{\pi^-}}{dz}) dz$
Sum of Kaon Multiplicities

- Contrary to pion case, here $D_s^{K-}, D_s^{K+}$ are dominant, larger than e.g. $D_u^{K+}$
- Since there are not too many $s, \bar{s}$ at high $x$, we should see some turn-on effect related to the increased density of strange quark PDFs at lower $x$
- Perhaps $x$ values accessed by COMPASS is too low to assure low density of $s, \bar{s}$

$$M^{K+} + M^{K-} = \int_{0.2}^{0.85} \left( \frac{dM^{K+}}{dz} + \frac{dM^{K-}}{dz} \right) dz$$
Multiplicity Ratios $\pi^-/\pi^+$ and $K^-/K^+$

[Graph showing multiplicity ratios for $\pi^-/\pi^+$ and $K^-/K^+$]
In the multiplicity ratio a lot experimental and theoretical uncertainties cancel.

In LO pQCD one can calculate a lower limit for the ratio

\[
R_K(x, Q^2, z) = \frac{dM_{K^-}(x, Q^2, z)/dz}{dM_{K^+}(x, Q^2, z)/dz} = \frac{4(\bar{u}+\bar{d})D_{fav}+(5u+5d+\bar{u}+\bar{d}+s+s)D_{unf}+(s+s)D_{str}}{4(u+d)D_{fav}+(5\bar{u}+5\bar{d}+u+d+s+s)D_{unf}+(s+s)D_{str}}
\]

\[
R_p(x, Q^2, z) = \frac{dM_{\bar{p}}(x, Q^2, z)/dz}{dM_p(x, Q^2, z)/dz} = \frac{(5\bar{u}+5\bar{d})D_{fav}+(5u+5d+2s+2s)D_{unf}}{(5u+5d)D_{fav}+(5\bar{u}+5\bar{d}+2s+2s)D_{unf}}
\]

\(D_{unf}\) is expected to be small at large \(z\), thus can be neglected.

\[
R_K = \frac{4(\bar{u}+\bar{d})D_{fav}+(s+s)D_{str}}{4(u+d)D_{fav}+(s+s)D_{str}}
\]

\[
R_p = \frac{\bar{u}+\bar{d}}{u+d}
\]

since \((s+s)D_{str}\) is positive, it can also be neglected for the lower limit calculation.

\[
R_K > \frac{\bar{u}+\bar{d}}{u+d}
\]

\[
R_p > \frac{\bar{u}+\bar{d}}{u+d}
\]

The lower limits predicted by LO pQCD for \(R_K\) and \(R_p\) are the same.

\(R_K\) is expected to be 10-15% higher than \(R_p\) because of \(D_{str}\).

\(R_{\pi}\) suffers from large contamination of decay products of diffractive \(\rho^0\).
Multiplicity Ratios $K^-/K^+$ and $\bar{p}/p$ from Isoscalar Target cont.

- Results published PLB 786 (2018) 390 and PLB 807 (2020) 135600
- At high $z$ multiplicity ratio for $K^-/K^+$ and $\bar{p}/p$ in data are below lower limits expected from pQCD in (N)LO
- Kaon results presented for $x < 0.05$
- Effect more pronounced for $\bar{p}/p$ and starts at lower $z$
SIDIS data are crucial for understanding quark fragmentation into hadrons
COMPASS already published several papers based on isoscalar data analysis
Today, results for $h^{\pm}$, $\pi^{\pm}$, $K^{\pm}$ multiplicities on proton target were shown
Impact of Radiative Correction is larger than originally anticipated in early isoscalar data analyses
Otherwise, there is a good agreement between proton and isoscalar data
Analysis is considered as finished - paper is in preparation